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Collaborative Robots' Perceived Safety
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Contents

1 Introduction

Human-robot interaction (HRI) represents a wide interdisciplinary research field with the purpose of understanding, designing, and evaluating robot systems which are used by or with humans. Interaction between robots and humans can take several forms, mostly depending on the distance between the human and the robot. In general, HRI can be divided into two categories: remote interaction (the human and the robot are spatially or temporally separated) and proximate interaction (the human and the robot are collocated; Goodrich & Schultz, 2007). HRI is defined as any kind of action that involves another human or a robot and does not necessarily serve a common goal. It is distinguished from human-robot collaboration (HRC), which is more specific and includes working with someone to reach a common goal (Bauer *et al.*, 2007).

2 Perceived robot safety

In an attempt to create safe HRI/HRC, two distinct types of safety need to be considered: physical safety and perceived safety (Lasota *et al.*, 2014). Physical safety can be divided into passive safety which encompasses safe mechanical design, and active safety which pertains to safety planning and control (Norouzzadeh *et al.*, 2012). A significant amount of work has been done to provide the current state of physical safety of collaborative robots, e.g., compliant mechanisms, safety peripherals, different protocols (for an overview, see Bartneck *et al.*, 2009). In this way, collaborative applications are thought inherently safe for the user. Different quantitative parameters ensuring safety are specified in standards, e.g. ISO/TS 15066 (ISO, 2016).

However, ensuring just physical safety is not sufficient to lead to stress-free and comfortable interaction for the human. Does the worker feel safe working alongside the robot? Is the robot perceived as a companion or as a dangerous tool? Are defined safety parameters, such as position, velocity, and force, causing discomfort to the worker? Regardless of the objective physical safety, it is of great importance that humans perceive the robot as safe since humans are less willing to work with a robot when they do not believe it is safe (Atkinson & Clark, 2014; Norouzzadeh *et al.*, 2012). Perceived safety reflects the user's perception of the level of danger when interacting/collaborating with a robot, and the user's level of comfort during the interaction/collaboration (Bartneck *et al.*, 2009). In past research, HRI/HRC safety from the user's point of view has been devoted significantly less attention compared to the aspects of physical safety.

Within a broader context, the perceived safety of robots can be considered an element of robot acceptability. Studies have focused on several parameters supposed to determine acceptability of robots, including user's emotions during HRI or HRC, such as fear and surprise, and perception of robot's attributes, such as appearance, movements, behaviour, and safety (for an overview, see Weistroffer *et al.*, 2013). In a recently developed Human-Robot Collaboration Acceptance Model (Bröhl *et al.*, 2019), perceived safety was established as one of the critical determinants of perceived ease of robot use, a dimension of robot acceptance along with perceived usefulness of the robot, behavioural intentions to use the robot, and robot use behaviour.

On the following pages, we present some of the studies that examined factors and metrics of perceived robot safety, different experimental setups, as well as some existing toolkits that evaluate different aspects of HRI/HRC. One of the main drawbacks of the existing studies is small sample sizes and heterogeneous measures that limit the comparability of their results.

3 Factors affecting perceived robot safety

Since our behaviour is frequently driven by how we perceive the world (You *et al.*, 2018), it is essential to know which factors affect an individual's perception of robot safety. The perception of robot safety is, among other things, influenced by the legibility of robot movements. Robot's behaviour is legible if a human can predict the next actions of the robot and the robot behaviour fulfils the expectations of a human interaction/collaboration partner (Lichtenthäler *et al.*, 2012). The ability to interpret and predict each other's actions helps people in everyday life to interact more smoothly with others. For example, it enables bicycle riders to avoid pedestrians in time (Takayama *et al.*, 2011). The same ability is also crucial in HRI and HRC since it allows humans to interpret and predict the robot's actions (Breazeal *et al.*, 2005). For example, even though a robot preparing a meal with very fast and unpredictable movements will successfully make a meal, a person might not feel safe around it as its actions are not understandable nor predictable (Lichtenthäler *et al.*, 2012). Such movements evoke negative emotions and psychophysiological reactions and consequently lower perceived safety by the user (e.g., Arai *et al.*, 2010; Dehais *et al.*, 2011). Studies have shown that people feel safer interacting with the robot if the behaviours of the robot are legible and take human movement into account (Lasota *et al.*, 2015; Lichtenthäler *et al.*, 2012). Animation principles mimicking natural human grasping motion were found to be related to higher legibility of robot movement (Papenmeier *et al.*, 2019; Takayama *et al.*, 2011). Purely functional motion can negatively affect task efficiency and user's perception of several aspects of the collaboration (Dragan *et al.*, 2015).

Specific robot parameters have been shown to increase perceived robot safety. Among the most investigated has been the speed of robot movement. Research has shown that high-speed movements result in a greater level of perceived hazard, higher task load and emotional reactions, and higher psychophysiological reactions compared to low-speed movements (Koppenborg *et al.*, 2017; Kulic & Croft, 2007; Or *et al.*, 2009). Adaptation mechanisms have been developed to adjust a robot's movement speed depending on human preferences and body signals (Mitsunaga *et al.*, 2008; Sisbot *et al.*, 2007). The perception of robot speed safety may also depend on the size of the robot. If the robot is smaller, the speed which is still perceived as safe by humans is higher than if the robot is larger (Duffy *et al.*, 2006; Rahimi & Karwowski, 1990), which is probably due to the notion that the movement of a larger robot (or any object) is more dangerous (Or *et al.*, 2009; Rahimi & Karwowski, 1990). The maximum speed, which is still perceived as safe is also higher if the starting speed of the robot is higher (Duffy & Or, 2006).

Furthermore, the robot movement trajectory may affect perceived predictability and safety of the robot. When a robot repeats the same sequence of movements to reach the target position, predictability should be high. However, predictability decreases when the trajectories of the robot's movements vary (Koppenborg *et al.*, 2017). In another study, participants reported more significant discomfort when the robot was blocking their path, when it was on a collision course with them, or when it was moving behind them (Koay *et al.*, 2005). However, another study revealed that participants' comfort ratings were higher if the robot used acoustic communication/signals when attempting to pass them from behind (Fisher *et al.*, 2014). Studies have also examined the perception of safe robot idle time, defined as the minimum amount of time that users would wait to consider that the robot stopped due to a malfunction rather than a programmed idle, and believed that the robot could be safely approached. Longer robot's halts may be wrongly perceived by users as malfunction stops instead of programmed stops, potentially leading to inappropriate and dangerous entries of users into the robot's working space. It was found that with larger robots, participants waited significantly longer before entering the robot operating area than with smaller robots (Or *et al.*, 2009). Regarding the effect of low vs high robot speed on the perception of safe robot idle time, studies conducted in real and virtual environments came to inconsistent conclusions (Or *et al.*, 2009; Rahimi & Karwowski, 1990).

Researchers were also interested in personal space in HRI, assuming that people would come closer to the robot when feeling comfortable and safe in their presence. A recent meta-analysis of these studies (Leichtmann & Nitsch, 2020) revealed that among robot-related factors of personal space in HRI robot appearance received the most attention in previous research. However, the results of these studies were inconclusive. While some found that people come closer to humanoid robots or human avatars compared to more mechanic-looking robots (Iachini *et al.*, 2014), others came to the opposite conclusions (Syrdal *et al.*, 2008) suggesting that distances to mechanic-looking robots could be shorter because they are not perceived as social beings with whom social norms apply. Previous studies also investigated the effects of speed and direction of the robot's approach into the user's personal space during HRI. Although one would expect that a high-speed approach or an approach from the back would be associated with higher perceived threat and thus smaller distance, studies came to inconsistent conclusions (for an overview, see Leichtmann & Nitsch, 2020). Additionally, no significant differences were found in the extent of personal space between studies in which the robot approached the human, and studies in which the human approached the robot. A study examining the impact of workspace sharing between humans and robots revealed that separation of the work area between a human and a robot facilitates perceived safety by promoting identification with human-robot team and trust in the robot (You *et al.*, 2018).

4 Experimental setups

In studies, where perceived safety was addressed, mainly two types of experimental setup were used:

a) using real robots already deployed in factories;
b) using simulations in virtual reality to remove any kind of danger for the users.

To best of our knowledge, there were no studies published where dedicated laboratory robotic setups were used to assess perceived safety.

4.1 Using real robots

Weiss and Huber in (Weiss & Huber, 2016) present the result of a case study on the user experience of an industrial robotic prototype in the context of human-robot cooperation in an automotive assembly line. In the collaborative application, the worker set screws on the motor block, the robot tightens them, and the worker performs the visual inspection. The operators working with the robotic prototype were interviewed three weeks after the deployment. The majority of participants expressed negative experience as the robot changed their way of doing the task of screw-tightening. As the robot system was very rigid without and way of adaptation, they experienced mistrust in low perceived safety.

In (Sauppé & Mutlu, 2015), the connection between acceptance and perceived safety was studied. Authors assessed perceived safety with workers working with robot Baxter in three different companies. The robot performed pick and place tasks together with the worker. The results indicate that social features that are already included in Baxter's design, such as its overall humanlike morphology and the behaviours displayed by its eyes and face, not only provide workers with a positive experience by eliciting feelings of safety and comfort but also improve manufacturing work by communicating cues that are necessary for successful coordination. However, increased sociality has the potential to create false expectations that may risk worker safety. Upgrading the robot to be seen as a co-worker and not a machine will make people feel safer around them.

Buchner with co-authors (Buchner *et al.*, 2012) studied the user experience with robots over time and connected perceived safety. The study included two different robotic systems: a) robotic cell with robotic arms already used for several years, where workers were prohibited from entering the robots' work area, and b) a newly introduced collaborative robot which was freely accessible. The questionnaires were filled two times with six months apart. Results have shown that the new robot was rated low regarding cooperation, perceived safety, perceived usability, stress, and general user experience shortly after deployment. After six months, the ratings for the new robot significantly improved, suggest that initial experience is positively affected by prolonged interaction.

In (Wurhofer *et al.*, 2015) authors test user experience as a critical factor for perceived safety and robot acceptance. The research included analysis of user experience at different stages of the robots' deployment in a factory. Authors identified three phases: a) anticipated experiences before the robot's deployment, b) initial experiences immediately after the robot's deployment, and c) long-term experiences in the daily work with the robots. The results have shown that before deploying the robot uncertainties, fear, scepticism, and rejection were predominant issues. After deployment and familiarisation with the robots, the shift in robot acceptance was detected as some of the fears that workers have has been identified as false.

4.2 Using virtual reality

Another way to assess perceived safety is by designing a virtual test environment. In virtual reality, it is possible to simulate impacts and malfunctioning without any danger for the users. Perceived safety can be tested by introducing different robots with variable speed and tools.

Authors in (Lichtenthaler *et al.*, 2012) presented a study of autonomous mobile robot's path affecting human perceived safety. Participants were presented with a video-based scenario in first-person perspective. The robot approached the human from different directions: left, frontal, or from the right. Participants were asked to rate prediction of the robot's behaviour and his/her emotional state regarding anxiety, agitation, and surprise. The result showed that the perceived safety is correlated with the prediction of the robot's behaviour

The study presented in (You *et al.*, 2018) was testing the impact of workspace sharing between worker and robot on perceived safety. In the study, participant and robot worked side by side on a construction site with a) separated workspaces divided by safety fence or b) shared workspace. The experiment included pre-questionnaire, interaction with the robot in the virtual reality, and postquestionnaire. The result showed that the degree of perceived safety is higher, with a greater separation distance between the worker and the robot by promoting team identification and trust in the robot.

5 Metrics of perceived robot safety

The question of how to evaluate the perception of the robot and its safety in HRI and HRC is difficult because human perception is a subjective concept. Different measures used in HRI/HRC research can be divided into three main categories: self-report questionnaires, physiological measures, and behavioural measures (Lasota *et al.*, 2014).

Subjective experiences of the robot and physical interaction/collaboration with the robot are most often evaluated with self-report measures, such as interviews or questionnaires composed of items with different response formats, such as Likert type rating scales or semantic differentials. Some questionnaires assess the perception of robot's attributes (e.g., Bartneck *et al.*, 2009), while others focus on the user's affective states as an indicator of perceived safety (e.g., Kulic & Croft, 2007; Nonaka *et al.*, 2004). However, the lack of standard questionnaires makes it challenging to compare the results from different studies. Besides, many questionnaires fail to meet minimum quality standards as they were developed ad hoc, and their psychometric characteristics have not been tested (Bartneck *et al.*, 2009).

Among the more common self-report measures used in HRI and HRC research is a non-verbal pictorial assessment technique called Self-Assessment Manikin (SAM; Bradley & Lang, 1994), which measures pleasure, arousal, and dominance associated with participants' emotional reaction to robots (e.g., Glojar *et al.*, 2011; Swangnetr & Kaber, 2013). Probably the most widespread psychometrically validated questionnaire is the Godspeed Questionnaire, which uses a 5-point semantic differential (anxious-relaxed, agitated-calm, and quiescent-surprised) for assessing perceived robot safety as one of the dimensions of the user's perception of robot's characteristics. It also measures anthropomorphism, animacy, likeability, and perceived intelligence (Bartneck *et al.*, 2009). User's discomfort level can also be measured with the Robotic Social Attributes Scale (RoSAS; Carpinella *et al.*, 2017) that was influenced by the Godspeed Questionnaire. The scale uses a 9-point Likert type scale to assess warmth, competence, and discomfort as central attributes implicated in human perception of robots.

Since self-reports can be susceptible to different interpretations of questions and to socially desirable responding, user's affective states in response to a robot can also be monitored through physiological reactions to a robot and its movements. Skin conductivity, skin temperature, heart rate, heart variance, blood pressure, respiratory rate, and pupil size respond to cognitive and emotional strain during the HRI or HRC. They are related to anxiety, fear, and stress (e.g., Kulic & Croft, 2007) indicating low perceived safety, which is why they were frequently used in studies on robot safety (Bartneck *et al.*, 2009) and robot acceptance (Weistroffer *et al.*, 2013).

Finally, perceived safety can be measured through observation of human behaviour in response to the robot. Behavioural measures also avoid self-reporting, but in contrast to physiological measures, they are often easier to analyse and interpret, since a variety of emotions can affect physiological signs and parameters. Therefore, a thoughtful selection of behavioural metrics can be a more direct and accurate measure of perceived safety. One of the prevalent behavioural measure used is the distance that the person maintains from the robot during HRI/HRC (Lasota *et al.*, 2014).

6 Toolkits for evaluating different aspects of HRI/HRC

An adequate evaluation of different aspects of HRI/HRC would enable a proper adaptation of the robot's behaviour, and this would result in making interaction or collaboration with a robot more comfortable for humans. Although there have been several attempts to develop theoretical frameworks with global or specific dimensions of HRI/HRC (e.g., Sanders *et al.*, 2011; Weiss *et al.*, 2009), they have rarely been validated with practical scenarios for studying the effects of different HRI/HRC factors, such as robots' shape and size. Recently, Rosen *et al.* (2019) developed human-related (i.e. strain, affective states) and technology-related criteria (i.e. dialogue principles, technology acceptance) and corresponding measures for the evaluation of the HRI quality and tested them in a preliminary laboratory study involving a manual assembly task accomplished with a lightweight robot. To assess the quality of the HRI, they compared the participants' strain and affective states before and after participating in the HRI scenario. The results revealed a decrease in positive affect and functional and dysfunctional strain after working with the robot, indicating an overall reduction in affective states. Also, the findings of the study suggested that some technology-related criteria can impact human-related criteria. In a study with elderly users, Heerink *et al.* (2010) established and tested a model of users' acceptance of assistive social robots, involving components such as perceived usefulness, perceived ease of use, and variables that relate to social interaction. The validity of the model was examined through a relationship of the model's components with intentions to use and actual use of the robot. The model explained 59–79 % of the variance in users' intentions to use the robot and 49–59 % of the variance in the actual use of it.

Studies on robot behaviour adaptation seek to adjust a robot's movement based on HRI constraints resulting in comfortable interaction for humans (Mainprice *et al.*, 2011; Mitsunaga *et al.*, 2008; Sisbot *et al.*, 2007). Mitsunaga *et al.* (2008) developed an adaptation mechanism that reads subconscious body signals from a human partner (i.e. gazing at the robot's face, human movement distance) indicating the human's comfort and discomfort, and uses this information to adjust interaction distances, gaze meeting, motion speed, and waiting time in human-robot interactions. Human-aware robot motion planner and control systems have also been developed that take into account several HRI constraints (e.g., safety, visibility, hidden zones) to achieve physical comfort for a human in HRI (Mainprice *et al.*, 2011; Sisbot *et al.*, 2007). Additionally, physical safety monitoring systems for collaborative robot applications have been proposed that maintain the system safety based on the user's motion (e.g., Byner *et al.*, 2019).

Since different methods for the assessment of perceived safety (i.e., self-report, physiological, and behavioural measures) differ in their essential qualities (Lasota *et al.*, 2014), a combination of different methods might provide an even better evaluation of human reaction to the robot in a specific HRC situation.

7 Standards relevant to the area

7.1 Robots in the industry

When using robot manipulator, either classical industrial manipulator or collaborative robot, in the industry, the mechanism and the cell that the robot is integrated into must comply with

- ISO 10218-1:2011 Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots;
- ISO 10218-2:2011 Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration.

Those two standards are currently under review (in the draft stage) and are planned to be replaced in the future by

- ISO/DIS 10218-1 Robotics — Safety requirements for robot systems in an industrial environment — Part 1: Robots;
- ISO/DIS 10218-2 Robotics — Safety requirements for robot systems in an industrial environment — Part 2: Robot systems, robot applications and robot cells integration.

These standards specify safety requirement for the industrial robot manipulators and also for their integration into industrial robot cells. Standard describes the primary hazards and hazardous situations identified within robot use and provides requirements to eliminate or adequately reduce the risks mentioned above.

When using collaborative robots, the additional technical specification should be considered:

- ISO/TS 15066:2016 Robots and robotic devices — Collaborative robots.

The document specifies safety requirements for collaborative industrial robot systems and the work environment, supplementing ISO 10218-1 and ISO 10218-2. Although this standard does not apply to non-industrial robots, presented safety principles can be transferred to other areas of robotics. This technical specification will be an integral part of future versions of ISO/DIS 10218-1 and ISO/DIS 10218-2.

To further expand the reach of ISO 10218-2, two additional technical recommendations should be taken into consideration:

- ISO/TR 20218-1:2018 Robotics — Safety design for industrial robot systems — Part 1: End-effectors;
- ISO/TR 20218-2:2017 Robotics — Safety design for industrial robot systems — Part 2: Manual load/unload stations.

Both of these two documents are important, considering safe interaction with humans. ISO/TR 20218-1 provides information on how to design and integrate robotic end-effectors safely. ISO/TR 20218-2 applies to manual load/unload applications – how to make it safe and ergonomically suitable for the worker.

7.2 Robots outside the industry

Although the majority of human-robot contacts happen in the industrial environment, other areas should not be neglected. The perceived safety of robots should be considered in any area where human-robot contact is unavoidable, e.g., personal care robots.

Standard

- ISO 13482:2014 Robots and robotic devices — Safety requirements for personal care robots

specify requirements and guidelines for the inherently safe design, protective measures, and information for the use of personal care robots. Personal care robots can be categorised into three types: a) mobile servant robot; b) physical assistant robot; c) person carrier robot. Collaborative robots, thus designed for industrial use, can also be integrated into any of the categories above.

The use of ISO 13482 can be further expanded by considering additional two technical recommendations:

- ISO/TR 23482-1:2020 Robotics — Application of ISO 13482 — Part 1: Safety-related test methods;
- ISO/TR 23482-2:2019 Robotics — Application of ISO 13482 — Part 2: Application guidelines.

The first document describes methods for testing the safety requirement of personal care robots. Appropriate tests are select by considering appropriate risk assessment. The second document is intended to facilitate the design of personal care robots in a way to allow close human-robot interaction and human-robot contact in personal care robot applications.

7.3 Robots in the virtual world

Virtual, augmented, and mixed realities (VR) are well connected with robotics within Industry 4.0 and also within the following Industry 5.0. Virtualisation has a vital role as enables testing of different scenarios of human-robot interactions that in the real world could be considered not safe.

Documents

- ISO/IEC TR 23842-1:2020 Information technology for learning, education and training — Human factor guidelines for virtual reality content — Part 1: Considerations when using VR content,
- ISO/IEC TR 23842-2:2020 Information technology for learning, education, and training — Human factor guidelines for virtual reality content — Part 2: Considerations when making VR content

should be considered when introducing the VR methodology to robotic systems for whatever reason (for testing dangerous applications, faster robot teaching, the better learning experience of first time robotic users, more intuitive service activities, etc.). These document present considerations for using VR content in the learning, education and training domain.

When designing a VR robotic cell, the best user experience should be provided and thus replicating as real-life like scenarios as possible. Documents

- ISO/IEC CD TS 23884 Information technology — Computer graphics, image processing and environmental data representation — Material Property and Parameter Representation for Model based Haptic Simulation of Objects in Virtual, Mixed and Augmented Reality (VR, MAR),
- ISO/IEC 18038:2020 Information technology — Computer graphics, image processing and environmental representation — Sensor representation in mixed and augmented reality,
- ISO/IEC 18040:2019 Information technology — Computer graphics, image processing and environmental data representation — Live actor and entity representation in mixed and augmented reality (MAR)

provide guidelines, how to represent objects, sensors and even human in the domain of VR. They define an exchange format between the virtual and physical world necessary for transferring data between the two. With such a framework, solid foundations are set where results from experiments done in the virtual world can be extrapolated to the physical world.

ISO 9241 Ergonomics of human-system interaction is a multi-part standard covering ergonomics of human-computer interaction. Parts most relevant to the area covered in this document are:

- 100 series: Software ergonomics
- 900 series: Tactile and haptic interactions.

Standard from 100 series

- ISO 9241-110:2020 Ergonomics of human-system interaction — Part 110: Interaction principles

describes principles for interaction between a user and a system and provides a framework for applying those principles to interactive systems design.

Standards from 900 series relate to the aforementioned capability to provide real-life user experience in the virtual world by addressing tactile and haptic interactions. Standard

- ISO 9241-910:2011 Ergonomics of human-system interaction — Part 910: Framework for tactile and haptic interaction

provides a framework for understanding and communicating various aspects of tactile/haptic interaction. It also provides guidance on how various forms of interaction can be applied to a variety of user tasks. This document and other standards from 900 series provide valuable information about how to enhance the telepresence feeling of the user and thus providing an accurate representation of the real world.

The document under ISO 9241 domain

- ISO/TR 9241-810:2020 Ergonomics of human-system interaction — Part 810: Robotic, intelligent and autonomous systems

addresses, among others physically embodied RIA systems, such as robots and autonomous vehicles with which users physically interact. In addition, it also considers the effect on users resulting from the combined interaction of several RIA systems such as conflicting behaviours between the RIA systems under the same circumstances. As such, it provides some critical insights that can be directly transferred to VR–enabled studies of human-robot interactions and safety.

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